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Quarterly Newsletter of the Institute for Computer Applications in Science and Engineering

Leon Clancy Receives NASA Awards

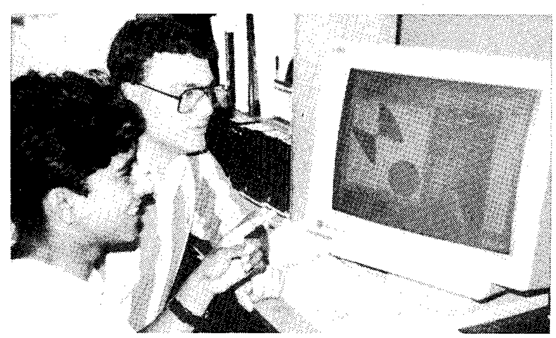
Leon M. Clancy, System Manager, was awarded a NASA Public Service Medal in a ceremony held at Langley Research Center on April 3, 1995. This award is the highest honor which NASA confers to non-government individuals, and was given *For significant contributions in developing a low-cost communications network that allows a practical High Performance Computing and Communications Education Outreach Program at NASA Langley Research Center.* Mr. Clancy is also a member of the HPCCP K-12 Educational Outreach Team which received a NASA Group Achievement Award for its work in developing Internet-based educational programs for school systems in eastern Virginia.

Left to right: A. Thomas Young, Leon M. Clancy, and Paul F. Holloway.

Best Mentorship Award

Shishir Mehrotra (pictured on the right) was given the Best Mentorship Project award by the New Horizons Governor's School. ICASE Staff Scientist David Banks (left) served as his mentor. The mentorship program involves some 70 high school students from the region. Students spend at least five hours a week with a mentor at a science-oriented institution. They propose projects, conduct research, and then present their results at the end of the school year.

Shishir studied 3D computer graphics and scientific data visualization. He wrote software to render images of 3D objects, and he tested high-end visualization systems to determine their usefulness for analyzing multivariate and unstructured scientific data.



Left to right: David Banks and Shishir Mehrotra.

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Use of the World Wide WEB at ICASE

*Leon M. Clancy**

Introduction

In July of 1993, ICASE began to use the World Wide Web (WWW). The Web is a collection of information servers on the Internet offering Hypertext documents written in Hypertext Markup Language (HTML). The Internet includes Commercial, Governmental, and Educational sites, all of which may participate in the Web by making HTML documents available through a Hypertext Transfer Protocol server (HTTP). Both HTTP and HTML are open and evolving non-proprietary standards offered for most computers.

Hypertext documents incorporate a structured method for defining the format of a document in a system-independent way. The document may include formatted text, graphics, and links to other Hypertext documents. Hypertext documents anywhere on the Web are referenced using a Uniform Resource Locator (URL). An example of a URL is the reference to the ICASE home page: http://www.icase.edu.

The large number of information sites on the Web created the need for sophisticated Web browsing and searching tools. ICASE initially chose Mosaic, one of the earliest graphical Web browsers available for all of our computers. Mosaic is a license-free application available from the National Center for Supercomputing Applications (NCSA). It can be accessed on the WEB at:
http://www.yahoo.com/Computers/World_Wide_Web/Browsers.

Mosaic offers an extremely friendly and powerful interface to the Web which is easily used by ICASE staff, visitors, and consultants to obtain up-to-date information about ICASE. Since the scope of the Web is worldwide, anyone using a browser is also allowed to access ICASE information deemed to be of interest to the general public.

Designing the ICASE Home Page

Web browsing usually starts with an anchor point known as the Home Page. The ICASE home page was created to make available the who, what, when, where and why of ICASE, in addition to our main research output of ICASE reports.

The ICASE home page is designed in such a way that information is provided and maintained by the responsible staff members. By structuring the home page to integrate the efforts of the staff, maintenance of the home page is divided into manageable portions, while retaining a unified appearance and direction. This avoids the need for a staff member dedicated to Web maintenance. Software tools, often Web based, are provided to the maintainers so that the input text may be converted to HTML and incorporated into the home page.

Building the ICASE Home Page

ICASE technical reports form the largest body of information we make available on the Web. Since all reports are approved for unlimited distribution, an ICASE report can be distributed via the Web to a world-wide audience.

In cooperation with NASA/Langley, ICASE report abstracts are full-text indexed and integrated with the Langley Technical Report Server (LTRS). The ICASE Technical Report Server is used to search and retrieve reports from our home page. Our part-time technical editor is responsible for final editing and reproduction of ICASE reports. A family of scripts was written that automate the process of adding the final report to the ICASE Technical Report Server. About 163 ICASE reports are now available through the Web, and about 7100 electronic copies have been downloaded through our server since December of 1993.

Another interesting use of the web at ICASE is the Colloquium announcement. The announcement itself has a simple notice consisting of the speaker's name, title, date, time, location, and abstract. The overall operation calls for announcement generation and mailing to our colloquium list about a week before the talk. A colloquium is added to the system by completing a web-based form that includes this information. On the morning of the colloquium, a short reminder message is then mailed to a list of people who have asked to receive colloquium announcements. At the time the announcement is generated, it is converted to HTML and placed in the ICASE Colloquium section of the home page. The announcement remains there until the day after the colloquium has been given, at which point it is moved to the Past Colloquia section. There, past announcements are viewable in reverse chronological order.

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There are a wide variety of web browsers, each of which has slightly different features and capabilities. One design goal for the ICASE home page has been to automatically recognize which browser is being used and provide a version of the ICASE home page that is adapted to the requirements of that browser. For instance, if the user has a text-only browser, then it is important to provide suitable substitutes for graphical information. Consideration has also be given to users with slow connections to the internet.

Using the Web inside ICASE

The Web at ICASE is used to distribute information to consultants, visitors, and staff members, as well as the world at large. Consultants and summer visitors use the web to obtain up-to-date information about ICASE when they arrive. A description of the local computing environment, visitor information and phone numbers, and miscellaneous information, such as paydays and holidays, are all available internally using a web browser.

The web provides a standard access method that allows visitors at ICASE to find the information they need quickly. Visitors come from a variety of computing environments and use the information presented via the web to acclimate themselves to the computing environment at ICASE.

The continuous influx of people at ICASE makes it necessary to quickly locate resident researchers. To this end, we are currently testing an online form to search for an ICASE staff member or consultant and bring up a map which will indicate his/her location within the building.

Figure 1 shows a Web page from the ITRS server at ICASE and illustrates the use of a search term to identify ICASE reports that contain keywords of interest to the user. The Netscape Web browser (found at the same location as Mosaic) was used in this example. The report title is underlined, denoting that it is a Hypertext link to the report itself. By selecting a link, the user may download the full text of the report for further research.

Usage Statistics

Statistics for the period May 19 through June 20, 1995 indicate that a daily average of 1474 files containing a total of 94Mbytes were transferred to Web users. This includes both internal and external use, but it indicates that the ICASE home page is being heavily used for its intended purpose.

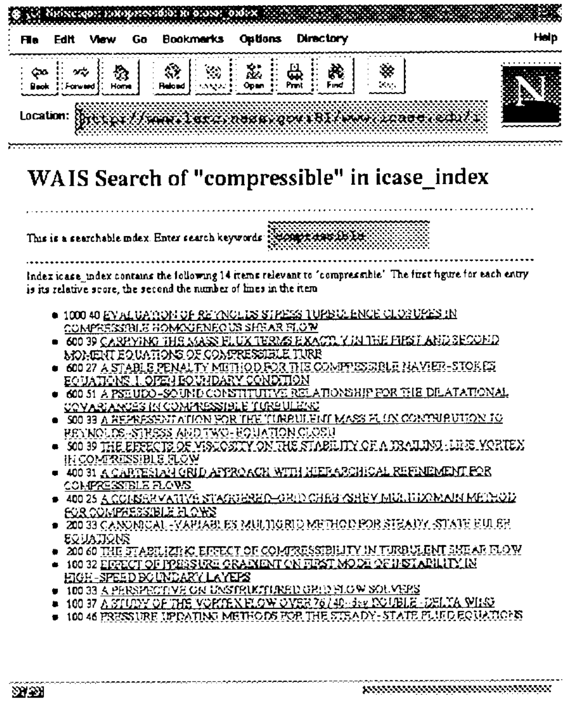

Figure 1: Example of a report search on the ICASE WEB.

Conclusions and Future Work

The World Wide Web has been expanding geometrically since ICASE began using it in 1993. National Public Radio reports that "about 1200 Web Servers are being added weekly." The Web has become an important method of sharing information to a large and growing audience of researchers.

The explosion in the number of computers connected to the Web has created a large market for Web servers and browsers with far more capability than originally anticipated. An important example is the Hot Java browser. Hot Java adds greater multi media capabilities. In order not to be "lost in the crowd," we see the need for the ICASE home page to be refreshed in terms of both look and content on an annual basis.

Researchers at ICASE have also been investigating the possibility of making multi media ICASE reports available. This will be practical only through the use of the Web. However, we will need to use the best available technology to provide highly compressed image, animation, and audio files to persons requesting them. A minute or two of full motion video with synchronized sound can easily exceed 10Mbytes.

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Infinite-Dimensional Optimization Problems

*Eyal Arian**

Introduction

In an infinite-dimensional optimization problem, the design variable is an element in a function space, as in the case of aerodynamics shape optimization problems. In practice, variables are discretized and the resulting maximum-dimensional problem is solved numerically. The size of the problem, including the number of design variables, depends on the level of refinement of the discretization. In the following, we discuss the analysis and numerical approach for solving such problems.

Discretization of the Design Space

When solving infinite-dimensional optimization problems numerically, it is customary to restrict the design space to a small and smooth finite-dimensional subspace, independent of the grid refinement. The major benefit of this approach is in a substantial reduction in the size of the Hessian, which greatly reduces the computational cost. In some cases it is possible to eliminate many of the constraints by a proper choice of the design space basis functions. On the other hand, restricting the design space to a small and smooth finite-dimensional subspace might become a disadvantage during the preliminary design phase since by doing so, one determines a priori the main features of the solution.

The difficulty in a direct discretization of the infinite-dimensional design space is that the resulting discrete problem contains approximately $M = N^{\frac{d-1}{d}}$ design variables, where N is the number of grid points in the computational domain, and d is the space dimension. Typically the Hessian, which is a rank M matrix, is dense and ill-conditioned. This typically causes slow convergence when using otherwise efficient low-rank Quasi-Newton methods such as the BFGS (an exception is the case where the Hessian's spectrum approaches zero continuously, i.e., is rank-deficient as will be discussed later in this article). Our purpose is to develop efficient numerical methods to solve such problems which can be applied without necessarily restricting the design variables to a small and smooth subspace.

Local Fourier Analysis of the Hessian

A local analysis is performed to identify the different categories of infinite-dimensional optimization problems and to serve as a tool in the development of efficient numerical schemes. The problem can be reduced to one on the boundary in Fourier space. High-frequency components of the errors in all the variables are considered in the analysis, which is a good approximation apart for a few frequencies in the lower part of the spectrum. Therefore, the analysis becomes more accurate as the mesh size decreases since the upper bound of the spectrum on a given grid, with mesh size h, is given by $\frac{\pi}{h}$ (for a uniform mesh in two dimensions).

The main goal of this analysis is to approximate the symbol of the Hessian operator, H, in the high frequencies near its minimum. Intuitively speaking, the different directions in the design space are spanned by the basis $e^{i\omega x}$, (x is the coordinate along the boundary of the designed surface), and the eigenvalues of the Hessian are given by the symbol $\hat{H}(\omega)$: $He^{i\omega x} = \hat{H}(\omega)e^{i\omega x}$. The condition number can be approximated by $\left(\frac{\pi}{h}\right)^{\gamma}$ where γ is the highest power of ω in $\hat{H}(\omega)$. Qualitatively we can differentiate between three classes of symbols: monotonically increasing ($\gamma > 0$), constant ($\gamma = 0$), and monotonically decreasing ($\gamma < 0$) functions of the frequency ω. The constant symbol problem is well-conditioned while the other cases are ill-conditioned and are either low-frequencies dominant ($\gamma < 0$) or high-frequencies dominant ($\gamma > 0$).

Let us elaborate on the different cases:

- In the case $\gamma > 0$ different "directions", $e^{i\omega x}$, have curvatures which are proportional to ω^{γ}. Therefore as ω varies from $O(1)$ to $\frac{\pi}{h}$, the curvature is changing dramatically, i.e., from $O(1)$ to $\left(\frac{\pi}{h}\right)^{\gamma}$. Taking the small disturbance shape optimization problem as an example, using the Euler equations and minimizing the pressure distribution on the surface to meet a desired target distribution, the leading term in the symbol $\hat{H}(\omega)$ is proportional to $|\omega|^2$. Therefore, this problem is expected to be highly ill-conditioned and high-frequency dominant.
- The case of a non-monotonic symbol, $\gamma = 0$,

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is relatively "easy" in the sense that conventional gradient-based algorithms will have very good convergence properties (the Hessian has a small condition number).

- The case of monotonically decreasing symbols, $\gamma < 0$, should be treated with care. In this case, high-frequency errors can enter the design variables resulting in a minor change in the cost functional (or the gradients). This is precisely the type of problem where the restriction of the design space to a small, smooth subspace is recommended. After eliminating this difficulty, Quasi-Newton methods should be efficient in solving this class of problems, since the low-frequency components only span a small-dimensional design space.

Note that the above analysis should be performed in the discrete space so the effects of a specific numerical scheme on properties of the Hessian are considered. Also, in nonlinear problems, the non-constant coefficients should be frozen resulting in a local approximation, $\hat{H}(\omega, x_0)$, where x_0 represents a point on the boundary.

Efficient Solution using Multigrid Methods

Multigrid methods are particularly attractive when solving an infinite-dimensional optimization problem since the design variables are updated on all levels as part of the multigrid solution of the analysis and adjoint problems (the "one-shot" method). The main difficulty is in providing a minimization algorithm which smoothes the design variables. If the Hessian is ill-conditioned and high-frequency dominant ($\gamma > 0$), we expect that the gradient descent iteration should smooth the errors in the design variables. In elliptic problems, a high-frequency change of a quantity which is defined on the boundary will result in a local effect close to the boundary; thus the solution should be updated only in a small neighborhood close to the boundary, resulting in a low cost functional evaluation on fine levels. Therefore, the solution of the optimization problem can be achieved at a cost of only a few solutions of the analysis problems.

The above ideas were tested numerically to solve various optimization problems including an optimal shape design problem in two dimensions, using a Poisson equation, where the design variables are the grid points along the boundary. The results show a fast convergence rate independent of the mesh size (See Figure 1).

Single Grid Preconditioning Methods

Sometimes it is desirable to have a method which can be applied when the analysis code is using one level of discretization. In that case, local Fourier analysis can be used to compute a preconditioned direction, $\mathcal{P}\nabla_u F$, which is a good approximation for the Newton direction in the high-frequencies. The preconditioner, $\mathcal{P}$, is computed such that its symbol approximates the inverse of the Hessian in the high-frequency regime: $\hat{\mathcal{P}}(\omega) \approx \hat{H}^{-1}(\omega \gg 1)$. In practice, the preconditioned direction should be projected onto the finite-dimensional design space.

The proposed algorithm uses two directions in each minimization step as is done in the trust region double dogleg algorithm. The two directions are given by the preconditioned direction, $\mathcal{P}\nabla_u F$, and a Quasi-Newton direction which accounts for the lowest frequencies. This method is currently under research.

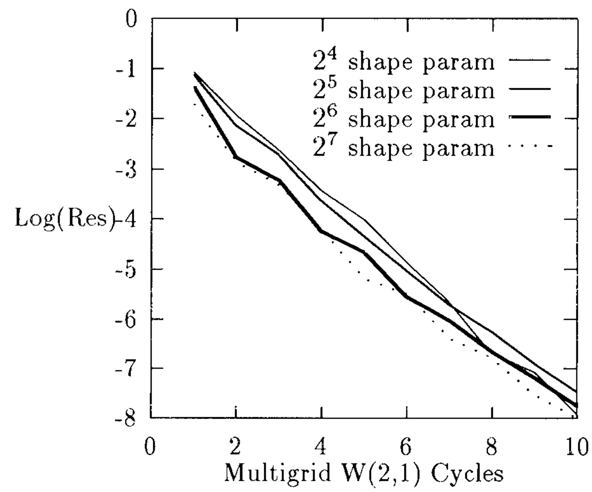

Figure 1. Convergence Rates for an Optimal-Shape Design Problem Using Multigrid Methods.

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A Model for Velocity Gradients in Homogeneous Turbulence

*Sharath S. Girimaji**
Charles G. Speziale†

Introduction and Modeling

The phenomenon of turbulence, it is generally agreed, is completely described by the Navier-Stokes equations. However, the Navier-Stokes equations have no known general analytical solution, and, even numerical solutions are possible for only the simplest of flow geometries at low Reynolds numbers. The objective of turbulence modeling is to devise an alternative set of tractable equations that mimic certain aspects of the turbulence phenomenon. Most models are phenomenological in nature and attempt to make quantitative predictions of turbulent flow statistics. There is another genre of models whose objective is to elucidate some physics of the turbulence phenomena without necessarily being quantitatively accurate. One such model is the restricted Euler equation (Vieillefosse [1], Cantwell [2]) given by

$$\frac{dA_{ij}}{dt} + A_{ik}A_{kj} - \frac{1}{3}A_{mn}A_{nm}\delta_{ij} = 0. \qquad (1)$$

where A_{ij} is the velocity gradient tensor and δ_{ij} is the Kronecker delta function. This model equation reproduces some important turbulent small-scale features frequently observed in direct numerical simulations (DNS) of isotropic and homogeneous shear flows. However, when the restricted Euler equation is compared against DNS databases for more complex turbulent flows, the agreement is not as good, especially in regions of moderate to low dissipation. This shortcoming may be due to the fact that it violates the balance of mean momentum for virtually all homogeneous turbulent flows with constant mean velocity gradients except isotropic and homogeneously sheared turbulence.

Recently, we have developed a modified version of the restricted Euler equation which satisfies the mean momentum equation for general turbulent flows and, hence, is better capable of simulating more complex test cases. For a detailed report of the material presented here, please see Girimaji and Speziale [3]. The modified restricted Euler equation for the total velocity gradients is given by:

$$\begin{aligned}\frac{dA_{ij}}{dt} &+ A_{ik}A_{kj} - \frac{1}{3}A_{mn}A_{nm}\delta_{ij} \\ &= \frac{d\overline{A}_{ij}}{dt} + \overline{A}_{ik}\overline{A}_{kj} - \frac{1}{3}\overline{A}_{mn}\overline{A}_{nm}\delta_{ij}.\end{aligned} \qquad (2)$$

A comparison of equations (1) and (2) reveals the difference between the original and the modified restricted Euler equation. In the modified restricted Euler equation model, the mean velocity gradient terms on the right-hand-side of equation (2) survive since the anisotropic mean pressure Hessian is not neglected — a feature that maintains consistency with the balance of mean momentum. The original restricted Euler equation is recovered for isotropic turbulence and homogeneous shear flow.

Results and Discussion

We solve the modified restricted Euler equation numerically for isotropic and anisotropic homogeneous turbulent flows. An ensemble of 4096 fluid particles is considered and the velocity gradient for each particle is obtained numerically by integrating the modified restricted Euler equation using a predictor-corrector Runge-Kutta scheme. We present the behavior of the the anisotropic structure tensor function defined as

$$F_{ij} = \overline{b_{ki}b_{kj}} - \frac{1}{3}\delta_{ij}. \qquad (3)$$

In the above equation $b_{ij} \equiv A_{ij}/\sqrt{A_{mn}A_{mn}}$. In isotropic turbulence, the components of these tensors are all zero. The magnitudes and signs of the non-zero components should therefore convey a good description of the anisotropic structure of the fluctuating velocity gradient tensor. We also examine some intrinsic properties of the velocity gradients. The results presented here are for the case of a rapid solid body rotation: $\overline{A}_{ij} = \omega\delta_{i1}\delta_{j2} - \omega\delta_{i2}\delta_{j1}$.

The time evolution of the diagonal components of the anisotropic structure tensor function F_{ij} is given in Figure 1. Rapid solid body rotation of an initially isotropic velocity field does not appear to affect the isotropy of the structure tensor function immediately. All three components stay close to zero initially for a short duration of time. This behavior is consistent with the observations from

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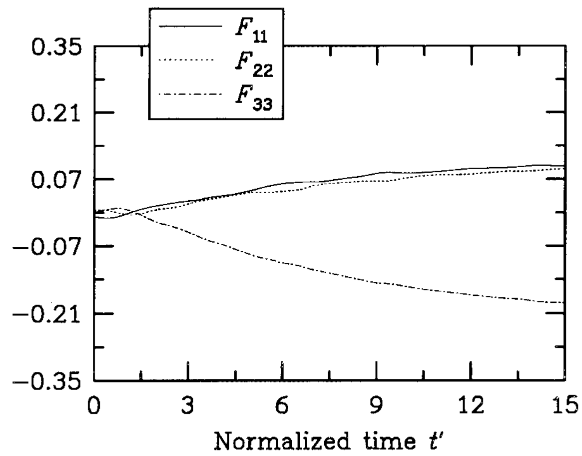

Figure 1: Time evolution of F_{ij} (new model).

the DNS of an initially isotropic velocity field subjected to a rapid solid body rotation. The DNS results indicate that rapid rotation produces inertial waves that scramble the turbulence and survive for several eddy turnover times leaving the velocity field with approximately isotropic one-point statistics. Once these inertial waves are damped, anisotropy due to mean rotation can set in. At later times, the axial component, F_{33}, starts to decrease (in comparison with F_{11} and F_{22}) gradually and monotonically, a feature that is consistent with the Taylor-Proudman theorem which calls for the axial velocity gradient to vanish at infinite rotation rate. The original restricted Euler equation, on the other hand, predicts that the axial component of the structure function tensor, F_{33}, increases with time, completely inconsistent with the Taylor-Proudman theorem (Figure 2).

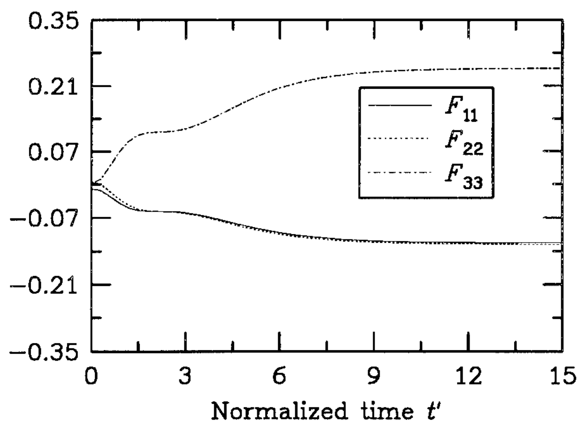

Figure 2: Time evolution of F_{ij} (old model).

Intrinsic geometry of b_{ij}.

Examination of DNS databases reveal that the intrinsic geometry of the fluctuating velocity gradients in anisotropic homogeneous turbulence is similar to that in isotropic turbulence. The eigenvectors of the strain-rate tensor are $\mathbf{a}_1$, $\mathbf{a}_2$ and $\mathbf{a}_3$, where the eigenvalues are arranged in descending order. Due to incompressibility, which renders the divergence of the strain rate rate zero, the largest eigenvalue is constrained to be positive and the smallest one negative. The modified restricted Euler equation, consistent with the original model and DNS findings, predicts that the vorticity vector is best oriented with the intermediate eigenvector ($\mathbf{a}_2$). The evolution of the averaged eigenvalues is given in Figure 3. The averaged intermediate eigenvalue is indeed positive, again consistent with DNS findings. Furthermore, these intrinsic properties are also preserved for both the homogeneous shear flow and plane strain flow cases which are not shown.

These results lead us to believe that the new modified restricted Euler equation can serve as a valuable dynamical model for the analysis of the geometry of the velocity gradient tensor in general homogeneous turbulent flows.

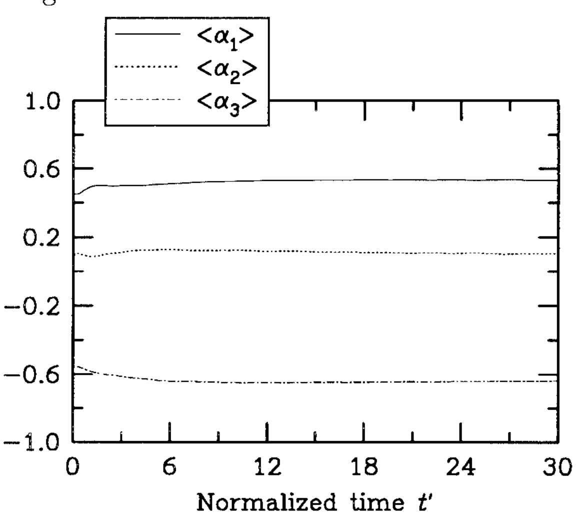

Figure 3: Time evolution of averaged eigenvalues.

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Numerical Simulations of Shock-Vortex Interactions

*Gordon Erlebacher**
Thomas L. Jackson†

In the late 1950's, Ribner began his study of shock/turbulence interactions. To this end, he considered a turbulent flow as a collection of linear waves which could be superimposed to form a resulting turbulent field. By studying the properties of a single wave interacting with a shock, he was able to deduce the effects of a shock on an upstream turbulent flow. Since then, there have been several studies seeking to extend Ribner's work. Thus, upstream acoustic and entropy waves were considered, and experimental work was initiated both to corroborate the theory, and extend it. Ten years ago, the first simulations were performed by Hussaini and his collaborators [1,2]. First with finite-difference methods, then spectral methods, and more recently back to high-order finite-difference methods, their studies mostly addressed the parameter range under which linear theory was expected to hold. Several nonlinear simulations of upstream entropy spots, vortex pairs and vortex streaks interacting with a shock were performed as well. However, downstream boundary-conditions were found to affect the results and thus, long-time integrations could not be performed. Furthermore, the quantitative study of nonlinear effects were never performed.

A related problem, which can be viewed as an important element of the more complex process of shock-turbulence interaction, is the interaction of a single vortex and a shock wave. This process is also of interest in aeroacoustics owing to the production of noise generated by shocks present in high-speed aircraft. Thus, in the second part of this work, the interaction of a single vortex and a shock wave is also investigated and compared to linear results. Results are presented for various vortex strengths and at various Mach numbers.

Although at the time, the primary motivation behind these studies was to understand the various types of amplification mechanisms of turbulence passing through a shock, recent work has focused on the acoustic properties of the sound generated when a vortex crosses a shock. Indeed, a single vortex produces an acoustic wave which propagates away from the vortex core at the speed of sound, and is responsible for the far-field noise measured by experimentalists.

We consider an ideal gas governed by the two-dimensional Euler equations in nonconservation form, supplemented with the equation of state for an ideal gas. The Euler equations are solved using a shock-fitted algorithm. To this end, two separate computational domains are required: one for the upstream region, and one for the downstream. Rather than construct a computational domain which abuts the downstream domain, we utilize the fact that the upstream (supersonic relative to the shock) flow is not affected by the shock motion. Therefore, all that is required to properly determine the downstream solution (including the shock position) is the upstream solution at the shock. In this way, the upstream solution can be calculated independently of the downstream solution. An evolution equation for the shock is derived by applying the Rankine-Hugoniot conditions to the downstream characteristic pointing into the shock, at the shock itself. Thus, both shock position and shape evolve in time. All spatial derivatives are computed using a compact 6^{th} order discretization scheme, with special treatment at the boundaries to maintain 6^{th} order accuracy. Time advancement is based on a low-storage, 5 stage, 4^{th} order accurate Runga-Kutta scheme. Instead of implementing a characteristic boundary condition downstream, we choose instead to construct a buffer domain. In this buffer, the Euler equations are modified to add a convective term to the time derivative whose role is to curve the characteristics in such a way that the characteristic velocities are all supersonic at the exit plane. Complete details are given in [2].

Although many studies have been made of shock/vortex interactions, there have been few quantitative studies of the nonlinear processes. It is known that for weak shocks, as the strength of the vortex increases, the shock develops a triple point, which has also been observed experimentally. However, there are instances where a triple point does not form and nonlinear processes are active nonetheless. To address this issue, we place a

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vortex with azimuthal velocity profile

$$v_\theta = \frac{\Gamma}{2\pi\sigma^2 e^{-0.5}}\, r\, e^{-0.5(r/\sigma)^2}$$

in the upstream domain. The pressure, density and temperature satisfy the isentropic relation $p = \rho^\gamma = T^{\frac{\gamma-1}{\gamma}}$. The analytical form of this vortex is an exact solution to the nonlinear Euler equations. We choose a core radius $\sigma = 0.3$, and study the effect of circulation Γ and shock Mach number M on the flow downstream of the shock. The radial exponential decay of all variables insures that spurious reflections will not occur from the freestream boundaries.

To identify nonlinear effects, we computed the RMS kinetic energy, pressure energy, vorticity and dilatation in the downstream domain, along with the dominant terms which contribute to their rate of change with time. All variables were normalized with Γ to insure that nonlinear effects manifest themselves as a departure from the time histories at infinitesimal Γ. We found that the dilatational energy quickly rises from zero to reach some maximum value shortly after the vortex crosses the shock. For moderate Γ, this rise is followed first by a short period of fast decay, which corresponds to the formation of the acoustic pulse and its initial separation from the vortex core. The ensuing slower decay is probably due to energy loss as the pulse propagates outward from the vortex center. As Γ increases, the pressure and dilatation "saturation" levels scale approximately as Γ^2. The scaling is not exact because a contribution of pressure is present due to the vortical field. It is clear that the Γ^2 scaling becomes more appropriate as the vorticity becomes stronger, and the downstream contribution of upstream pressure begins to dominate that of the pressure due to the upstream vortical modes. Note that a theory capable of making this prediction must be at least taken one step beyond linear. We have performed a high Mach number asymptotic expansion of the linearized Rankine-Hugoniot conditions, followed by a second expansion in the vortex circulation. The analysis reveal that nonlinear effects dominate the flow once $\Gamma M >$ constant. Moreover, the quadratic dependence of the downstream perturbation pressure on the shock Mach number is not the result of a finite-pressure inside the upstream vortex, but rather is due to the nonzero density inside the vortex, due to imposed isentropic conditions. Finally, as the circulation is increased to $\Gamma = 1$, we note that the dilatational energy begins to increase in time. We hypothesize that this is due to the steepening of the acoustic pulse as it radiates away from the vortex core. This is further evidenced by the two-dimensional plots shown in Figure 1. Another effect of nonlinearity is the destruction of the quadrupole structure of the acoustic pulse. As seen from the low Γ contours, the pressure field (and the dilatation) have a quadrupole structure. The two negative lobes have merge as the circulation increases, and the symmetry with respect to the $y = 0$ axis has disappeared. More figures and details are available in [2].

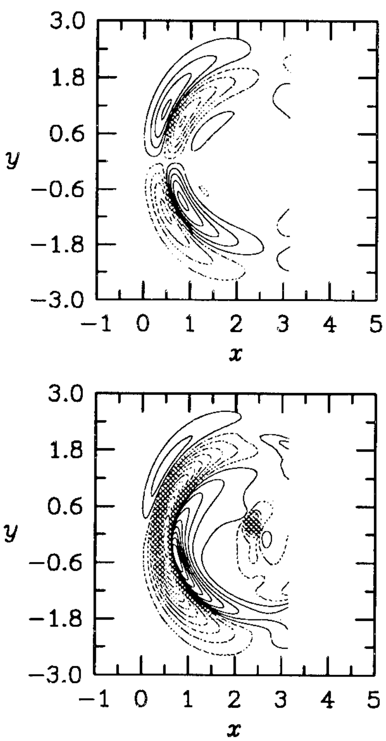

Figure 1: Contour lines of pressure. Mach 8 shock, $\Gamma = 0.03$ (top) and $\Gamma = 1.0$ (bottom). Negative values are dotted, positive values are solid.

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ICASE Colloquia

April 1, 1995 - June 30, 1995

Kremer, Ulrich, Rice University, "Automatic Data Layout for High Performance Fortran," April 7.

Bilger, Robert, The University of Sidney, Australia, "Conditional Moment Closure Methods for Complex Kinetics in Turbulent Combustion," April 7.

Kalns, Edgar T., Michigan State University, "Scalable Data Redistribution Services for Distributed-Memory Machines," April 10.

Wolkowicz, Henry, University of Waterloo, Canada, "A General Framework for Trust Region Subproblems with Applications to Large-Scale Minimization," April 13.

Krantz, Alan, International Institute of Applied System Analysis, Laxenburg, Austria, "An Efficient Algorithm for the Hard-Sphere Problem," April 14.

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